Quantitative field spectroscopic measurement instrumentation and techniques

Schaepman, Michael E ; Dangel, Stefan ; Kneubühler, Mathias ; Schläpfer, Daniel ; Bojinski, Stephan ; Brazile, Jason ; Kötz, Benjamin ; Strub, Gabriela ; Kohler, R ; Popp, C ; Schopfer, Jürg ; Itten, Klaus I

Abstract: Over the past few years imaging spectrometer have increased in number and quality significantly. Directly correlated to this growth, is the need of (near-) simultaneous field work with non-imaging spectroradiometers. Due to severe constraints in technology requirements for these field instruments (portability, power supply, etc.), reliable portable instruments have become available later than their imaging correspondents. The systematic use of a large variety of ground instruments from their early stages in 1990 and onwards is therefore discussed and the need for reproducible radiometric measurements outlined. The assessment includes a review of calibration practices for non-imaging instruments and examples of sampling strategies needed for field data collection. Finally, a combined measurement facility (FIGOS/LAGOS) is presented, demonstrating the usefulness of measuring bi-conical reflectance factor under laboratory conditions (LAGOS, Laboratory Goniometer System), and its outdoor counterpart measuring hemispherical-conical reflectance (FIGOS, Field Goniometer System).

Quantitative Field Spectroscopic Measurement Instrumentation and Techniques

M. E. SCHAEPMAN, S. DANGEL, M. KNEUBÜHLER, D. SCHLÄPFER,
S. BOJINSKI, J. BRAZILE, B. KÖTZ, G. STRUB, R. KOHLER, CH. POPP,
J. SCHOPFER, and K. I. ITTEN
Spectroscopy Lab, Remote Sensing Laboratories, Dept. of Geography,
University of Zurich, Switzerland. e-mail: *schaep@geo.unizh.ch*

Abstract. Over the past few years imaging spectrometer have increased in number and quality significantly. Directly correlated to this growth, is the need of (near-) simultaneous field work with non-imaging spectroradiometers. Due to severe constraints in technology requirements for these field instruments (portability, power supply, etc.), reliable portable instruments have become available later than their imaging correspondents. The systematic use of a large variety of ground instruments from their early stages in 1990 and onwards is therefore discussed and the need for reproducible radiometric measurements outlined. The assessment includes a review of calibration practices for non-imaging instruments and examples of sampling strategies needed for field data collection. Finally, a combined measurement facility (FIGOS/LAGOS) is presented, demonstrating the usefulness of measuring bi-conical reflectance factor under laboratory conditions (LAGOS, Laboratory Goniometer System), and its outdoor counterpart measuring hemispherical-conical reflectance (FIGOS, Field Goniometer System).

1. Introduction

Spectroradiometry is the technology of measuring the power of optical radiation in narrow wavelength intervals. The consistent reproduction of such complex spectra depends closely on high quality measurement instrumentation. Difficulties associated with such measurements are strongly dependent on the presence of high technology measurement equipment and appropriate calibration strategies. Reliable measurement of spectroradiometric quantities is still fraught with difficulties and calibration issues remain partly unsatisfactorily resolved. The quantitative characterization of these constituents is the goal of spectroradiometry in remote sensing.

Even though recent advances in technology, sampling strategies, and calibration have a significant impact on the quality of the uncertainty in measurements, it remains that:

Spectroradiometric measurements are one of the least reliable of all physical measurements (Kostkowski, 1997).

Three major reasons for large errors in spectroradiometry are:

The measurement is a multidimensional problem,

The instability of measuring instruments and the standards used to calibrate these instruments are frequently 1% or more during the complete measurement process, and

The principles and techniques used for eliminating (or reducing) measurement errors due to this multidimensionality or instability have not been widely disseminated.

In addition to the above, the contributing sources to a spectroradiometric measurement under solar illumination are complex and a detailed understanding of the individual processes are required to allow an unambiguous identification of the measured object (see Figure 1).

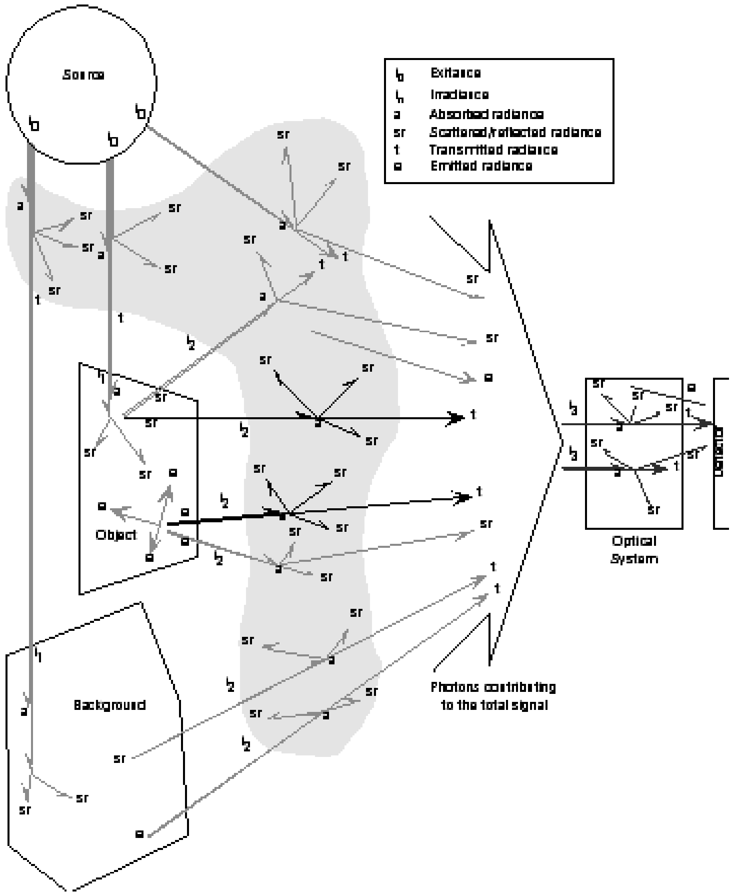

Figure 1 Contributing sources to a spectroradiometric measurement (Schaepman, 1998).

It has been widely accepted that spectroradiometric measurements must be accompanied by a high quality statement of uncertainty to improve their usefulness and reusability for further analysis. The following graph lists the quantities involved in spectroradiometric measurements and depicts the evolution of an individual measurement into a final result including its associated variance (c.f., Figure 2).

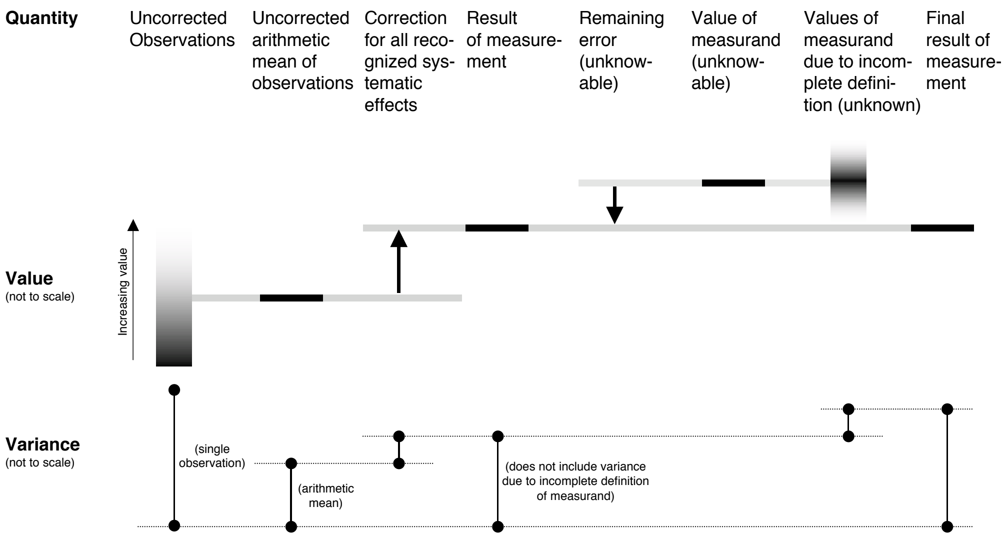

Figure 2 Values, errors and uncertainties (ISO, 1995).

After having performed a suitable quantity of calibration measurements, all the sources of uncertainty are taken into account and can be represented as traceable measurements to a standard. In the case of Figure 3, the visualized results are given for a GER3700 absolute radiance calibration and only the detector transition area (from a Si detector to a PbS detector) is listed. In this case the calibration has been performed including a temperature correction, to account for thermal uncertainties in the SWIR detector material.

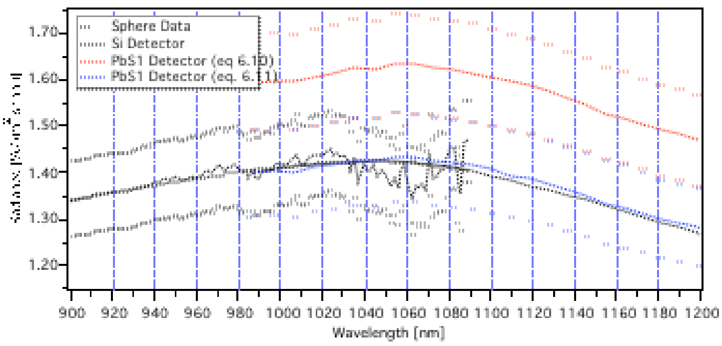

Figure 3 Reporting of absolute radiance calibration including all remaining uncertainties (Schaepman, 2000).

Since most of the field spectroscopic measurements are performed in reflectance, Figure 4 lists a traceable reflectance calibration for the same instrument. The relatively large uncertainty in reflectance originates from the assumption that the atmosphere is changing between the reference (Spectralon) measurement and the corresponding (homogenous) target.

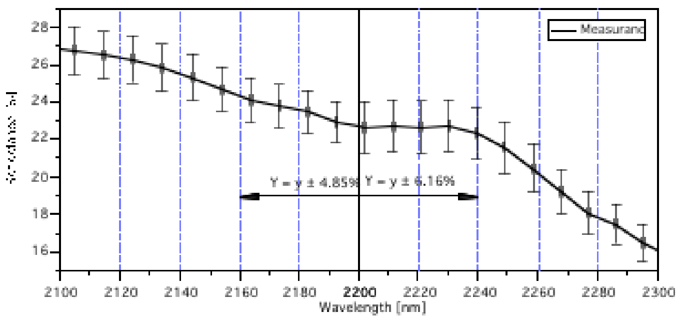

Figure 4 Reporting of traceability to a standard (e.g., NIST) in reflectance including the expanded uncertainties (Schaepman, 1998).

For quantitative spectroscopic measurements it is crucial to determine the required calibration accuracy because it helps to estimate the calibration effort needed and can also be a helpful measure to define the required recalibration frequency. Any spectroradiometric measurement device tends to drift over time. These drifts generally introduce a higher uncertainty over time and therefore the overall calibration accuracy might suffer from inappropriate recalibration intervals.

2. Measurement Plan

The successful selection of an appropriate calibration strategy relies on many factors, which need to be determined before the actual calibration begins. Different users have different ideas about the calibration effort. For more technically oriented scientists, the full characterization of the instrument is the primary interest, whereas an applied user typically has concerns about algorithm robustness for the calibration uncertainty.

A full laboratory calibration is the most cost and time effective calibration. The accuracy desired from this type of calibration must be carefully determined in advance in order to assure user satisfaction. There is a fundamental difference in selecting a calibration strategy for uncertainties of 1% or 10%. Many calibration standards do not supply an uncertainty of 1% or less simply because their traceability to a primary standard degrades over time because of ageing of the lamp standard. In addition, it might be important to measure many quantities in a very short period for a 1% calibration to avoid drifts associated with the measurement process. Both are very cost-efficient processes in terms of resources and money. It is therefore important to set up a measurement plan that provides a high level of detail for which quantity is to be measured and how the measurement is performed.

The measurement plan is therefore the *key cost and success factor* for any calibration and contains in its simplified form at least the description of the following elements:

Detailed description of the quantity to be measured including the accuracy desired,

Identification of potential error sources and their estimation of their magnitude (can also be according to specifications or literature search),

Selection of the radiance standard,

Selection of the spectroradiometer,

Select the wavelength standard,

Characterize the spectroradiometer for all potential errors,

Select and characterize the measurement set-up,

Select the measurement design,

Acquire the data and calculate the quantity desired, and

Prepare the uncertainty report and report on all sources of uncertainty.

A detailed description of a measurement plan for a laboratory calibration is discussed in Schaepman (1998, 2000).

3. RSL SpectroPool

Over the past few years, RSL has established a spectrometer pool with various ground-based measurement instrumentation. The instrumentation is grouped into the following categories[1]:

Calibration and verification instrumentation and standards,

Field deployable spectroradiometers, and

Sun photometers.

[1] Reference herein to any specific commercial product, process, or service by trade name, trademark, service mark, manufacturer, or otherwise does not constitute or imply endorsement, recommendation, or favouring by RSL.

3.1. Calibration and Verification Instrumentation and Standards

Integrating spheres are widely used to calibrate spectroradiometric measurement devices. Several types of measurements such as diffuse reflectance, specular reflectance and diffuse transmittance can be performed using an integrating sphere. In general an integrating sphere is a hollow sphere which has its interior coated with a substance that is nearly perfectly diffuse or lambertian. For accurate radiance calibration of a spectroradiometer, the sphere as a source of uniform radiation as a secondary standard is used. The RSL integrating sphere (see Fig. 6) consists of a source module/optics head and a separate electronic display console/power supply. This enables remote location of either unit, which facilitates alignment or positioning of the source with respect to the device to be calibrated (Optronics, 2002).

Spectralon diffuse reflectance standards are calibrated and traceable to The National Institute of Standards and Technology (NIST). Each is supplied with diffuse reflectance data from 250 nm to 2500 nm, in 50 nm increments. Optional intervals are available. Spectralon diffuse white standards offer the highest diffuse reflectance values of any known substance. These durable, chemically inert and washable standards have typical reflectance values of 95% to 99% and are spectrally flat over the UV-VIS-NIR spectrum. All Spectralon materials are typically flat to ±4% over the range of 250 to 2500 nm and ±1% over the photopic region of the spectrum. Spectralon reflectance standards and materials are highly lambertian over their effective spectral range.

Spectralon wavelength calibration standard sets consist of three wavelength calibration standards covering the UV-VIS-NIR region of the spectrum. Each wavelength standard is formulated by impregnating a Spectralon substrate with the oxide of a rare earth element that displays sharp absorption spikes at specific wavelengths. Complete absorption spectral data is supplied with each standard (Labsphere, 2002).

The three standards available are:

Holmium Oxide, for UV-Vis-NIR calibration,

Dysprosium Oxide, for NIR calibration, and

Erbium Oxide, for Vis-NIR calibration.

These durable, washable and chemically inert standards are ideal for wavelength calibration of spectrometers.

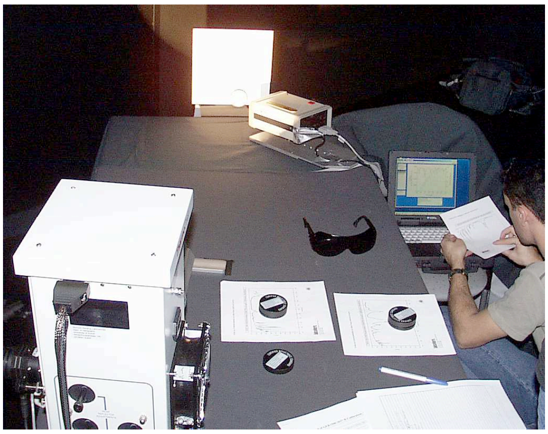

Figure 5 Combined reflectance/wavelength calibration using Spectralon reflectance and wavelength standards.

Finally the illumination standard is a 1000 W quartz tungsten halogen lamp in a research housing. The housing is equipped with a F/0.7 four-lens element condenser and is supplied by a radiometric power supply (Oriel, 2002). In addition to this, a light intensity control system monitors the intensity of the inside of the housing with a silicon-based sensor (see Fig. 6, right). The lamp is also used to illuminate the targets measured with LAGOS.

Figure 6 Radiance calibration: Integrating sphere standard (left) and calibrated 1000W FEL lamp (right).

3.2. Field-Deployable Spectroradiometers

Field spectrometer measurements allow for the spectral characterization of natural or artificial targets, such as vegetation, soil, water, or asphalt. They are also used to calibrate and validate airborne or spaceborne spectral data, providing ground truth for vicarious comparison. Field spectrometers themselves need to be calibrated at regular intervals to provide reliable and reproducible spectral data as mentioned before.

In most applications at RSL, target reflectance is of primary interest, that is the ratio between reflected radiance, integrated over a given spatial angle, and incoming irradiance. The latter can be derived by employing a well-known, near-Lambertian Spectralon panel as a reflectance standard. Although long-term trends in the spectrometers' properties are cancelled out in the reflectance data, instrument degradations can lead to a decreased signal to noise ratio in individual spectral bands. Additionally, ageing of detectors can give rise to shifts in the centre-wavelength position of spectral bands. Absolute radiance calibration is mainly required for the calibration and validation of airborne/spaceborne sensors. Radiance based vicarious calibration is one of the most challenging applications for field spectroradiometers, since the portability of the instrument (and therefore its size and weight limitations) has a significant impact on its radiometric uncertainty.

All RSL spectroradiometers are calibrated on a regular basis for the following parameters:

Linearity of detector responses at different radiation levels,

Signal-to-noise ratio,

Noise-equivalent signal,

Noise-equivalent radiance,

Position of centre-wavelength for each band,

Absolute radiance calibration, and a

Qualitative comparison of reflectance signatures for different targets.

The spectroradiometers available are listed in the table below (Table 1). Usually the spectrometers ship with a calibration performed before their delivery. Typically, a calibration is guaranteed for one year.

Instrument	Spectral range [nm]	Number of Bands	Field of view [deg]	Purchased
GER1500-2036	302.16-1107.52	512	3	1998
GER1500-2037	314.17-1101.16	512	3	1998
GER3700-0002	298.45-2504.12	704	2.2-16	1995
ASD FSFR	350.0-2500.0	2151	25	1998

Table 1 Overview and configuration of RSL spectroradiometers (ASD, 2002), (GER, 2002).

The following Table 2 lists the spectral band characteristics, as published on the companies' websites, after initial calibration. Indicated wavelengths are given as spectral band centre-wavelengths according to the last calibration. The three ASD detectors may overlap as well, but the signal of the corresponding bands is used for resampling and the final data product has no overlap or gaps.

	Spectral resolution (sampling interval)	Band # of 1st detector wavelength range	2nd detector	3rd detector
GER1500 2036	1.5 nm @ 350-1050 nm	# 1-512 302.16-1107.52 nm	-	-
GER1500 2037	1.5 nm @ 350-1050 nm	# 1-512 314.17-1101.16 nm	-	-
GER3700	1.5 nm @ 350-1050 nm 6.2 nm @ 1050-1900 nm 9.5 nm @ 1900-2500 nm	# 1-457 298.45-998.43 nm	# 458-526 (orig. 515-583) 1007.16-1888.32 nm	# 527-647 (orig. 584-704) 1908.25-2504.12 nm
ASD FSFR	3 nm @ 700 nm (1.4 nm @ 350-1050 nm) 10 nm @ 1400, 2100 nm (2 nm @ 1000-2500 nm)	# 1-649 350-999 nm	# 650-1449 1000-1799 nm	# 1450-2151 1800-2500 nm

Table 2 Spectral band characteristics and detector transitions of calibrated spectroradiometers.

Figure 7 Field spectroradiometers (from left: ASD FieldSpec FR, GER1500, GER3700). The GER1500 is also available in a dual-FOV configuration with an underwater box for in–situ water measurements.

3.3 Sun–Photometers

Two instruments are in use for measuring solar irradiance, the University-of-Arizona ‘Reagan’ sun-photometer and the YES MFR–7 shadowband radiometer.

The Reagan sun-photometer is a sun-looking ground-based instrument for atmospheric measurements. In Remote Sensing applications it is mainly used for atmospheric measurements in order to improve atmospheric correction algorithms. It therefore is used as atmospheric ground-truthing instrument in field campaigns. Its continuous monitoring of the state of the atmosphere allows furthermore conclusions on atmospheric stability and daily developments of aerosol contents. Cross calibration with other instruments will help to evaluate their performance (UofA, 2002).

The Multi-Filter Rotating Shadowband Radiometer (MFR-7) is a field instrument that simultaneously measures global, diffuse, and direct normal components of spectral solar irradiance. The MFR-7 uses independent interference filter-photodiode combinations, mounted in a temperature-controlled enclosure, to detect spectral irradiance at six wavelengths and in one broadband channel. The choice of wavelengths allows the reconstruction of the incident solar spectral irradiance and the determination of optical depths of water vapor, aerosols, and ozone. The MFR-7 consists of two basic components: a Detector Assembly and an Electronics Enclosure (YES, 2002).

Figure 8 Sun photometers (Univ. of Arizona Reagan Sun-photometer (left), YES Multiband Shadow Radiometer (right)).

4. RSL GonioPool

The **Fi**eld-**Go**niometer **S**ystem (FIGOS) was initially designed based on ideas from Klaus Itten and Stefan Sandmeier, and consequently built by Willy Sandmeier at Fa. Lehner & Co. AG, Gränichen, Switzerland, in a joint effort with the Remote Sensing Laboratories (RSL) at the University of Zurich, Switzerland (Schaepman, 1994; Sandmeier, 1995; Itten, 2002). FIGOS is a transportable field goniometer operated using a PC-controlled GER-3700 spectroradiometer. It covers the electromagnetic spectrum between 400 and 2500 nm in 704 bands with a calibrated full-width at half maximum (FWHM) of 2.2 nm (400–1100 nm), ~11 nm (1000–1900 nm), and ~14 nm (1900–2500 nm) respectively (Schaepman, 1998 & 2000).

The goniometer consists of three major parts: a zenith arc and an azimuth rail, each of 2 m radius, and a motorized sled where the sensor is mounted. All parts of FIGOS are made of black-coated aluminium, resulting in a total weight of only 230 kg. The complete goniometer system is stored and transported on a trailer with a specifically designed interior, allowing fast and convenient access to a field site (see Fig. 9). About 90 minutes are needed for the set-up of the goniometer with a team of two people. For transportation the azimuth rail and the zenith arc are disassembled. Mounting of the zenith arc is provided by sleds connected to the azimuth rail that allow a full 360° rotation. The ball bearings of the wagons embrace the azimuth rail in a way that the zenith arc is tightly fixed so that measurements can be taken even on sloped terrain.

A support linking the center of the zenith arc with the azimuth rail provides further stabilization and helps to guide the cables. In order to enable measurements in the solar principal plane, the zenith arc is mounted eccentrically on the azimuth rail, and only the radiometer itself moves in the principal plane. Since the radiometer's instantaneous field-of-view is rather small, nominally ~2.7° (rectangular image of the slit), and always pointing to the center of the hemisphere, shadow on the target area only occurs when the radiometer is aligned with the sun in the backscatter direction. Therefore, hot spot measurements are not possible with the current mounting of the radiometer. In the present configuration, the sensor's footprint is about 10.5 cm (in its longest extent) in nadir direction and about 41 cm (major axis) in the most extreme view zenith angle position of 75°. Thus, the radiometer is always viewing approximately the same surface area in the center of the hemisphere. The sled with the spectroradiometer mounted is driven by a 24 V DC braking motor, and a precision chain serves as a guideway for the 3/8" cogwheel. The motor velocity is set to 2.5°/sec. Fully adjustable labels on the zenith arc allow for an automated positioning of the spectroradiometer. It is also possible to drive the sled-motor manually from a remote control unit to any desired position on the zenith arc between -75° and +75°. Positioning precision on the zenith arc is within ±0.2°.

FIGOS is currently being used in RSL's darkroom where measurements without the influence of diffuse illumination conditions can be taken (Fig. 9). Whilst using FIGOS in the laboratory, the name is changed to Laboratory Goniometer System (LAGOS).

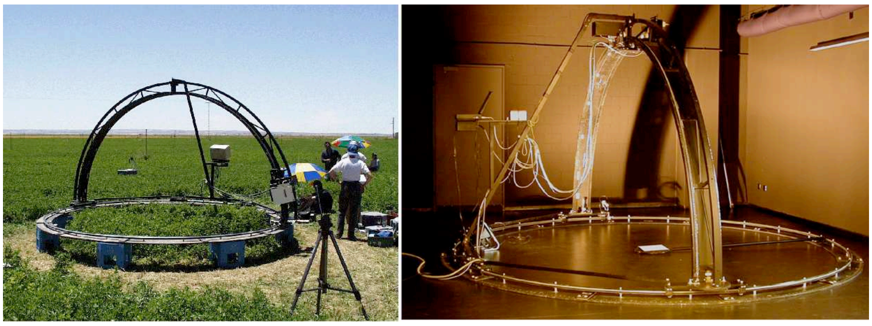

Figure 9 FIGOS (left) in use at the DAISEX'99 campaign (Berger, 2001) and LAGOS installed at RSL.

Normalization of measured spectro-directional data is a means to analyze the spectral variation of the BRDF. Reflectance data from each view angle are divided by a standard reflectance signature in order to obtain relative deviations. An optimal standard reflectance signature is the spectral albedo as inherent property of the object, which can be derived from the BRDF. For unknown anisotropic behavior of the target, the albedo has to be approached by hemispherical reflectance (Strub, 2001) or nadir reflectance, thus generating the so-called ANIF (see Fig. 10).

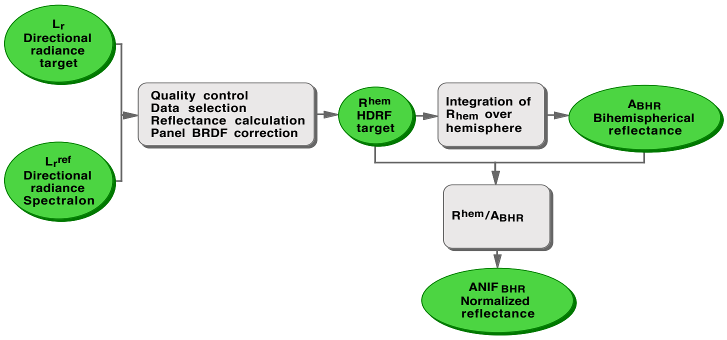

Figure 10 FIOGS measured and derived parameters (BRDF: Bidirectional Reflectance Distribution Function, HDRF: Hemispherical Directional Reflectance Factor, BHR: Bihemispherical Reflectance (Albedo), ANIF: Anisotropy Factor).

An example of measured ANIF distribution for alfalfa, for two view angles, is shown in the figure below.

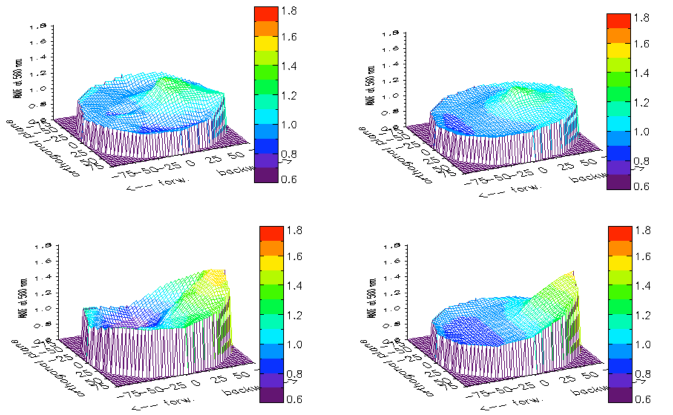

Figure 11 FIOGS measured and simulated (SAIL/PROSPECT) polar plots of anisotropy factors at 560 nm.

5. Conclusions

In quantitative Earth observation, calibration is an essential task. Calibration needs and efforts have been underestimated for a long time, but since they gained more attention, methods and accuracies have improved significantly. Nevertheless, it is inappropriate to define a set of calibration parameters once in the lifetime of a spectroradiometric measurement instrument. Also there is no calibration strategy available that automatically generates calibration coefficients as a function of time. As a consequence, the interference of scientists will always be required to calibrate this kind of instrument. Discussion over calibration effort versus calibration accuracy can only be resolved satisfactorily if the figures of merit for a calibration are normalized so that they allow a transparent comparison with other instruments. In addition, predictable accuracies, or at least model-able ones, are required to determine the extent of the calibration effort.

Certainly there are limitations to the calibration effort. Laboratory calibration reduces the operational time of the instrument and binds many resources to the calibration process. After the laboratory calibration the instruments needed for the laboratory calibration are—in the worst case—not accessed until the next recalibration task. Inefficient resource allocation and ageing of the calibration instrumentation introduces even higher costs to the calibration effort.

When it comes to the comparison of calibrated instruments, or even when trying to evaluate and acquire instruments, the figures of merit must be clearly defined to allow for a proper estimation of an instrument's capability.

Three major issues of concern are still to be resolved:

Most of the collected field data are still in reflectance—radiance measurements are scarce.

Instrument calibration data volumes and efforts may easily exceed field acquired data volumes and times.

The cost of a single calibrated spectrum is still not a negligible amount.

6. Acknowledgements

The spectrometer and goniometer pool is supported by the University of Zurich, and the Swiss National Research Foundation (Project–No. 2000-061431.00/1).

7. References

ASD, http://www.asdi.com, 23 April 2002.

Berger, M., Moreno, J., Müler, A., Beisl, U., Richter, R., Schaepman, M., Strub, G., Stoll, M. P., Nerry, F., Leroy, M., Rast, M., Wursteisen, P., and Attema, E.: The DASIEX campaigns in Support of a Future Land Surface Processes Mission. ESA Bulletin 105, February 2001, pp. 101-111.

GER, http://www.ger.com/ground.html, 23 April 2002.

ISO, Guide to the Expression of Uncertainty in Measurement, Intl. Org. for Standardization, Switzerland, pp. 101, 1995.

Itten, K., Schaepman, M., Strub, G., and Beisl, U.: The Field Goniometer System (FIGOS)—A Field Deployable BRDF Measurement Facility, In: Schönermark, M. (ed.): 'Reflection properties of Vegetation and Soil with a BRDF Data Base', accepted for print, 2001.

Kostkowski, H. J., *Reliable Spectroradiometry*, Spectroradiometry Consulting, La Plata, MA, pp. 609, 1997.

Labsphere, http://www.labsphere.com/products/products.asp?CID=37&PID=378, 23 April 2002.

Optronics, http://www.olinet.com/spctrl_rad_lum.htm, 23 April 2002.

Oriel, http://www.oriel.com, 23 April 2002.

Sandmeier, St., Sandmeier, W., Itten K.I., Schaepman, M.E. and Kellenberger, T.W.: The Swiss Field-Goniometer System (FIGOS). In: Proc. of IGARSS'95, Firenze, Vol. III, p. 2078-2080, 1995.

Schaepman, M., Sandmeier, S., Itten, K.I., Meyer, P., and Kellenberger, T.: Spectral Signature Analysis Using a Field Goniometer Mounted Spectroradiometer. 1st Intl. Airborne Remote Sensing Conference, ERIM, Vol. II, Strasbourg, p. 171–177, 1994.

Schaepman, M.: *Calibration of a Field Spectroradiometer—Calibration and Characterization of a Non-Imaging Field Spectroradiometer Supporting Imaging Spectrometer Validation and Hyperspectral Sensor Modelling*. Remote Sensing Series, Vol. 31, Dept. of Geography, University of Zurich, pp. 155, 1998.

Schaepman, M. and S. Dangel, "Solid laboratory calibration of a nonimaging spectroradiometer," Appl. Opt. 39, 3754-3764 (2000).

Strub, G., Keller, J., Schaepman, M., Beisl, U., and Itten, K.: Comparison of modeled and measured diurnal directional reflectance data of an alfalfa canopy. Proc. ISPRS Commission VII, Workshop on Spectral Signatures, Aussois, pp. 285-290, 2001.

UofA, http://www.optics.arizona.edu/rsg/, 23 April 2002.

YES, http://www.yesinc.com/, 23 April 2002.